Giant Andreev Backscattering through a Quantum Point Contact Coupled via a Disordered Two-Dimensional Electron Gas to Superconductors

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We have investigated the superconducting-phase-modulated reduction in the resistance of a ballistic quantum point contact (QPC) connected via a disordered two-dimensional electron gas (2DEG) to superconductors. We show that this reduction is caused by coherent Andreev backscattering of holes through the QPC, which increases monotonically by reducing the bias voltage to zero. In contrast, the magnitude of the phase-dependent resistance of the disordered 2DEG displays a nonmonotonic reentrant behavior versus bias voltage. [S0031-9007(97)04427-X]

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How is the resistance of a ballistic quantum point contact (QPC) modified when it is connected to a superconductor? We can answer this question if we recognize that electrons injected through a QPC will return through this QPC as positively charged holes after being Andreev retroreflected at the normal-superconductor (NS) interface [1,2]. This effectively doubles the current at the same bias voltage and consequently reduces the QPC resistance by a factor of 2 compared to its quantized value in the normal state $R_{\mathrm{QPC}} = h/2e^2N$, with N the number of propagating modes [3].

However, the above holds only for clean normal conductors, where transport in the region between QPC and superconductor is ballistic. When disorder is present in this region, the reflected holes will be scattered. Classically, ignoring phase-coherence, the particles have an equal probability of returning through the QPC as electrons or holes due to multiple Andreev reflections. As a result the QPC resistance is equal to its normal-state value. Surprisingly, calculations [4] have shown that *coherent* Andreev backscattering through a QPC in series with a disordered normal conductor is not destroyed. The term "giant" Andreev backscattering has been introduced, since the probability for injected electrons to return through the QPC as holes can approach unity when the resistance of the QPC dominates over that of the disordered normal conductor.

Observation of this giant Andreev backscattering requires that the device dimensions are small compared to the phase-breaking length ℓ_ϕ. Second, the elastic mean free path ℓ_e should be smaller than the distance L between QPC and superconductor, but larger than the QPC dimensions to ensure ballistic transport through the QPC itself. Third, the NS interface should be highly transparent. Finally, the excitation energy of electrons (temperature T or bias voltage V) should be comparable to the Thouless energy $E_T \equiv \hbar D/L^2$ (with diffusion constant D) to maintain coherence between injected electrons and returning holes [5].

In this Letter, we investigate electron transport in a device consisting of two QPC's attached via a disordered two-dimensional electron gas (2DEG) to two superconductors (see Fig. 1). The bias-voltage dependence of superconducting phase-dependent resistances enables us to distinguish the reduction in resistance of the QPC from that of the disordered normal conductor.

The 2DEG is hosted in an InAs layer of an InAs/AlSb heterostructure. The fabrication process is identical to that described in Ref. [6]. The AlSb top layer is removed, which reduces the elastic mean free path to about $\ell_e \simeq 0.2\ \mu$m. Note that in Ref. [7] the top layer was left intact, which allowed the study of *ballistic* transport between QPC and superconductor ($\ell_e > L$). Insulating trenches in the 2DEG are defined by electron-beam lithography and wet chemical etching. Finally, the patterned 2DEG is connected to superconducting terminals by Ar milling the exposed InAs surface *in situ* [8] in order to obtain highly

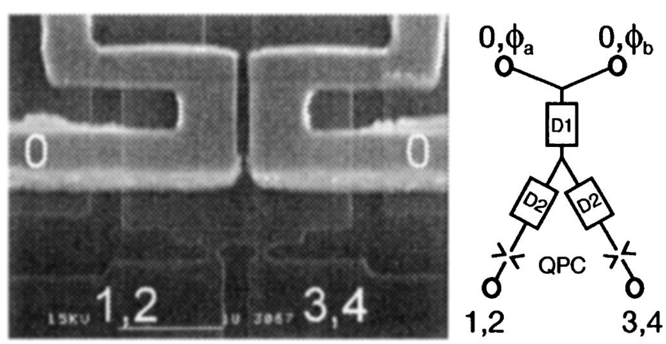

FIG. 1. Scanning electron micrograph of an interrupted superconducting loop (0) connected via a disordered 2DEG and two ballistic QPC's to normal leads (1, 2, 3, and 4). The drawing represents an equivalent circuit consisting of diffusive resistors D1 and D2 and ballistic QPC's.

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transparent interfaces with the subsequently deposited 50 nm niobium terminals.

A micrograph of a device is shown in Fig. 1. The bright regions represent the superconducting terminals (0), which are parts of an interrupted superconducting loop. The magnetic flux Φ through this loop determines the difference in superconducting phase between both terminals: $\varphi = 2\pi\Phi/\Phi_0$, $\Phi_0 \equiv h/2e$ being the superconducting flux quantum. The distance between a QPC and the superconducting terminals is about 0.8 μm, which exceeds several times ℓ_e, implying that in this region transport is diffusive. The lateral width W of the left and right QPC are about 90 and 110 nm, respectively ($W < \ell_e$). The number of populated quantum channels ($N = k_F W/2$) in the QPC is estimated to be 8 and 10, respectively, given the electron density of $n_s \simeq 1.2 \times 10^{16}$ m^{-2}.

We have investigated two nominally identical devices at a temperature of 180 mK using cryogenic filtering [6]. The ballistic nature of our point contacts is confirmed by the analysis of the magnetoresistance similar to that presented in Ref. [7]. In this method, the Sharvin resistance of a ballistic QPC is obtained from the reduction in the longitudinal magnetoresistance due to the suppression of geometrical backscattering from the QPC constriction [9]. The measured reduction is about 1.5 kΩ for the left QPC and 1.3 kΩ for the right QPC, which is in good agreement with the values 1.6 and 1.3 kΩ, respectively, as estimated from their widths. The remaining longitudinal resistance of about 0.5 kΩ is due to diffusive transport and corresponds to the sum of the resistance of the disordered 2DEG between QPC and superconductor of approximately 0.3 kΩ and a series resistance from the QPC to the leads of 0.2 kΩ. This latter contribution is most likely not fully phase coherent and will be regarded as a classical Ohmic series resistance.

The multiterminal geometry allows us to investigate the dc bias-voltage dependence of the differential resistances for two configurations, namely $R_{30,40}$ ($R_{10,20}$) and $R_{30,10}$ ($R_{10,30}$), where the indices label the current and voltage contacts, respectively (see Fig. 1). We will refer to the first configuration as a "two-terminal" resistance, which measures the resistance of the ballistic QPC in series with the resistance of the disordered 2DEG between QPC and the superconductor. The "three-terminal" resistance is obtained by using the second QPC as a voltage probe and measures a fraction of the resistance of the disordered 2DEG.

Figure 2 displays three traces at increasing bias voltages (from top to bottom) of the two-terminal magnetoresistance $R_{30,40}$ in Fig. 2(a) and of the three-terminal magnetoresistance $R_{30,10}$ in Fig. 2(b). All resistance traces contain an oscillating contribution with a magnetic field period corresponding to a superconducting-phase difference of 2π. The magnetic field also penetrates the area of the disordered 2DEG between the QPC's and the superconducting terminals. A magnetic field of about ± 40 G introduces sufficient phase shifts to destroy coherence between electrons and holes.

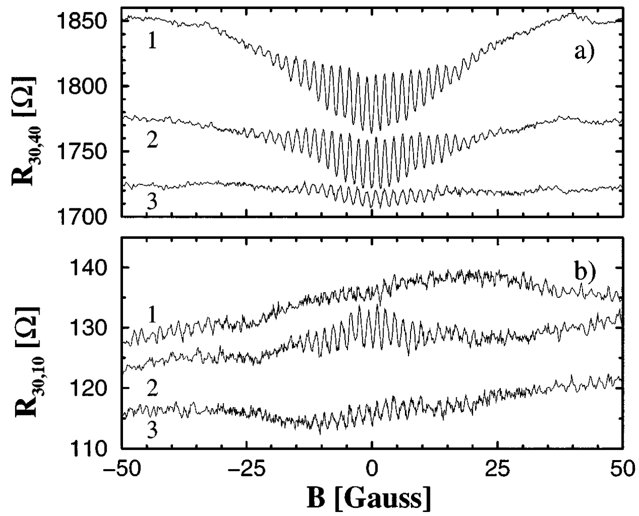

FIG. 2. The upper panel (a) displays the two-terminal magnetoresistance $R_{30,40}$ at applied dc-bias voltages of (1) 0 mV, (2) 0.14 mV (offset $= -40\ \Omega$), and (3) 0.45 mV (offset $= -50\Omega$) at a temperature of 180 mK. Panel (b) displays the simultaneously measured three-terminal magnetoresistance $R_{30,10}$, where trace 3) was offsetted by $+15\ \Omega$.

The total reduction in the two-terminal resistance $R_{30,40}$ due to coherent quantum interference is defined as the reduction in resistance at $B = 0$ G ($\varphi = 0$) with respect to its normal-state value at $B = \pm 40$ G. The full bias-voltage dependence of this total reduction in resistance and of the magnitude of the resistance oscillations is displayed in Figs. 3(a) and 3(b), respectively. Both the total reduction and the magnitude of the oscillations exhibit a maximum at *zero bias voltage*.

The presence of (reproducible) sample-specific fluctuations in the three-terminal magnetoresistance $R_{30,10}$ prohibits an accurate determination of its normal-state value at $B = \pm 40$ G. Therefore, we studied the bias-voltage dependence of the oscillations in $R_{30,10}$, which around $B = 0$ G are in phase with the oscillations $R_{30,40}$. This indicates that they are not dominated by sample-specific transport [6]. The bias-voltage dependence of the magnitude of the oscillations in $R_{30,10}$ shows a remarkably different behavior. Their magnitude exhibits a maximum at a *finite bias voltage;* see Figs. 2(b) and 3(c). At lower and higher bias voltages their magnitude decreases and becomes comparable to the sample-specific conductance fluctuations modulated by the superconducting phase [6]. We verified that $R_{10,20}$ and $R_{10,30}$ showed a similar behavior.

Transport in a disordered normal conductor coupled to a superconductor has been described theoretically by an energy and position-dependent diffusion constant [10,11]. This effective diffusion constant returns to its normal-state value at both zero and high energies and is enhanced for energies of the order of the Thouless energy ($E_T \simeq$ 0.11 meV for our geometry). The energy dependence of

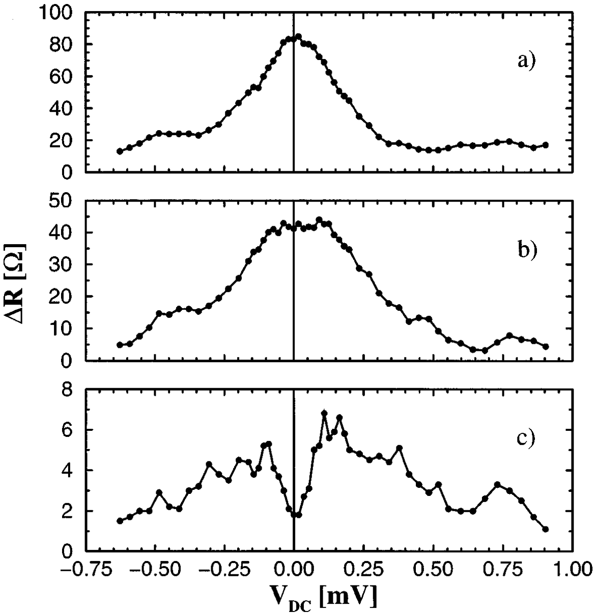

FIG. 3. Bias-voltage dependence of the reduction in resistances at 180 mK. Panel (a) displays the total reduction in the two-terminal resistance $R_{30,40}$ obtained by subtracting the resistance at 0 G from that at ±40 G. Panels (b) and (c) show the magnitude of the resistance oscillations around 0 G of the two-terminal resistance $R_{30,40}$ and the three-terminal resistance $R_{30,10}$, respectively. Panels (a) and (b) demonstrate coherent Andreev backscattering through a ballistic QPC after traversing a disordered conductor, whereas the resistance of the disordered conductor itself exhibits a reentrant behavior as shown in panel (c).

the resistance thus displays a reentrant behavior, which has recently been confirmed experimentally [6,12] and is also observed in the magnitude of the three-terminal resistance oscillations as displayed in Fig. 3(c). We conclude that the relevant energies in our experiment can be reduced well below E_T.

The two-terminal resistance $R_{30,40}$ displays at bias voltages below E_T a completely different behavior than the three-terminal resistance. Namely, the total reduction and the magnitude of the oscillations in $R_{30,40}$ do not exhibit a reentrant behavior for bias voltages below 0.1 mV. This excludes an interpretation based on a network of diffusive conductors. Therefore, we have experimentally confirmed that the reduction in the two-terminal resistance predominantly originates from the QPC resistance, which is modified due to giant Andreev backscattering [4].

We proceed with analyzing calculated resistances for the two-terminal and three-terminal configuration. We employ the circuit theory [11], which is based on the Keldysh Green's function formalism. In this theory, the mesoscopic conductor is represented as a circuit consisting of diffusive conductors, tunnel barriers, or quantum point contacts, which can be connected to normal and superconducting reservoirs. A spectral current is introduced, which depends on the difference in spectral angle θ across a conductor. Normal reservoirs are described by $\theta = 0$ and superconducting reservoirs by $\theta = \pi/2$ and a superconducting phase φ. At zero energy the spectral currents are $I = G_N\theta$ for a diffusive conductor, $I = G_N \sin\theta$ for a tunnel barrier, and $I = G_N 2\tan(\theta/2)$ (with $N \gg 1$) for a QPC, where $1/G_N = R_N$ denotes the normal-state resistance. The spectral current should be conserved at the circuits nodes, which determines the spectral angle θ_n at the node. The renormalized Andreev resistances are given by $R_A = R_N$ for a diffusive conductor (*no renormalization at zero energy*), $R_A = R_N/\cos\theta$ for a tunnel barrier and $R_A = R_N\cos^2(\theta/2)$ for a QPC.

Coherent Andreev backscattering through a QPC can be described within this framework by considering a circuit of a QPC with resistance $R_{\rm QPC}$ in series with a disordered conductor with resistance R_D connected to a superconductor [4]. The total Andreev resistance R_A is

$$R_A = R_{\rm QPC}[\tfrac{1}{2}(1 + \cos\theta_n)] + R_D\,,$$

where

$$\theta_n = \pi/2 - \frac{R_D}{R_{\rm QPC}}[2\tan(\theta_n/2)] \quad \text{with } \theta_n \in (0, \tfrac{\pi}{2})\,.$$

When $R_{\rm QPC}$ increases, θ_n shifts towards $\pi/2$ to conserve the spectral current. Consequently, the difference in spectral angle across the QPC increases, which results in an enhanced reduction of the QPC resistance. Note that when $R_{\rm QPC} \gg R_D$, the QPC resistance is reduced by a factor of 2. This illustrates the giant Andreev backscattering of holes returning through the QPC with unit probability.

The above picture for zero energy remains valid at finite energies, however, the spectral angle develops an imaginary component. In Fig. 4 the calculated energy dependence is plotted for the reduction in the two-terminal resistance [Fig. 4(a)] and the three-terminal resistance [Fig. 4(b)]. We inserted the following values for the normal-state resistances in the circuit depicted in Fig. 1: $R_{D1} = 0.1$ kΩ, $R_{D2} = 0.2$ kΩ, and $R_{\rm QPC} = 1.3$ kΩ [13]. In Figure 4(a) the solid line represents the reduction in the two-terminal resistance. Note that this reduction is equal to the difference in resistance at $\varphi = 0$ and $\varphi = \pi$ (its normal-state value in this model). The QPC resistance (dotted line) shows a reduction of about $0.3R_{\rm QPC}$ for energies below $1.4E_T$, which clearly dominates the contribution of the disordered conductors R_{D1} and R_{D2} (dashed line). Figure 4 shows the reduction in the three-terminal resistance. As expected a full reentrant behavior is obtained, where the maximum reduction in resistance of about $0.38R_{D1}$ occurs around $2.0E_T$.

The results of the calculations qualitatively describe the experimentally observed bias-voltage dependence for both the two- and three-terminal resistances. However, the measured two-terminal resistance shows only a reduction of about $0.06R_{\rm QPC}$. When we would assume that the

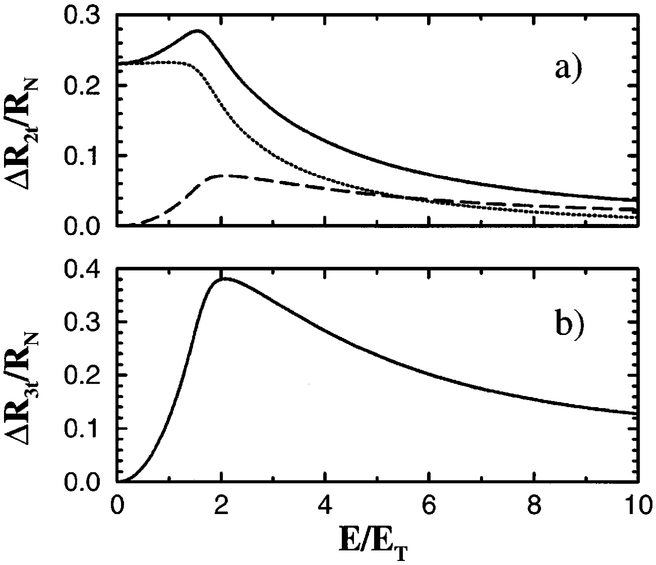

FIG. 4. The calculated energy dependence for the reduction in the two-terminal resistance R_{2t} (a) and three-terminal resistance R_{3t} (b) compared to their normal-state values R_N. The reduction in R_{2t} (solid line) is equal to the sum of the reduction in the QPC resistance R_{QPC} (dotted line) and the reduction of the diffusive resistance $R_{D1} + R_{D2}$ (dashed line), whereas the reduction in R_{3t} is equal to the reduction in R_{D1}.

series resistance from the QPC to the leads of 0.2 kΩ is fully phase-coherent (which is very unlikely), the calculated reduction would be lowered to $0.2R_{\mathrm{QPC}}$, which is still larger than experimentally observed.

An improved agreement might be obtained when two-dimensional diffusion in the disordered 2DEG is taken into account. In our devices the finite time scale of transverse diffusion cannot be ignored [4,14]. Second, the NS interface is not abrupt as assumed in the calculations, but should be considered as a coplanar NS contact. Third, we assumed in the calculation that all electrons carry the same energy. However, in the experiment a second normal reservoir with a reduced electrochemical potential is present, which injects electrons at lower energies. Finally, the theory assumes that the ballistic QPC is spatially separated from the disordered region [14], whereas experimentally scatterers close to the QPC are not excluded.

In conclusion, we have shown experimentally that coherent Andreev backscattering through a QPC enhances its conductance at zero energy, despite the presence of disorder in the 2DEG between QPC and superconductor. In addition, we have demonstrated that the enhanced QPC conductance decreases monotonically with increasing bias voltage and does not show a reentrant behavior, in contrast to the resistance of the disordered 2DEG.

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[13] We simplified the circuit of Fig. 1 to a single QPC with $\mathcal{R}_{\mathrm{QPC}} = 0.65$ kΩ connected via a single diffusive conductor with $\mathcal{R}_D = 0.2$ kΩ to two superconductors. The two and three-terminal resistances can be expressed as $R_{2t} = 2\mathcal{R}_{\mathrm{QPC}} + 1.5\mathcal{R}_D$ and $R_{3t} = 0.5\mathcal{R}_D$.

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